Report for 2002ID13B: Physically Based Models for Hydraulic Properties of Swelling Soils

- Water Resources Research Institute Reports:
  - NA
- Conference Proceedings:
  - NA
- Articles in Refereed Scientific Journals:
  - Tuller, M., and D. Or, 2003. Hydraulic Functions for Swelling Soils: Pore Scale Considerations. Journal of Hydrology, 272:50-71.
- Dissertations:
  - NA
- Book Chapters:
  - NA
- Other Publications:
  - Tuller, M., D. Or, and B. Muhunthan, 2002. Theoretical and experimental studies on retention and transport properties of swelling porous media. Abstracts of the INRA-INEEL Subsurface Science Symposium, October 13-16, Boise, Idaho. Tuller, M., D. Or, and B. Muhunthan, 2002. Evolution of textural pore space of clay-sand mixtures under variable water potential: Experimental studies on water retention and saturated flow behavior. SSSA Annual Meeting Abstracts, November 10-14, Indianapolis, Indiana.

Report Follows

Problem and Research Objectives:

Some of the most productive agricultural soils contain appreciable amounts of active clay minerals and exhibit shrink-swell behavior in response to changes in soil water content and chemical composition of the soil solution. Swelling and dispersion of clay minerals modify hydraulic soil properties and lead to increased surface runoff with negative impacts on water quality of rivers and lakes. Furthermore, cracks forming in dry clay soils provide fast preferential pathways for rapid transport of chemicals leading to potential risks for ground water contamination. In addition to myriad agricultural management and engineering problems associated with changes in mechanical properties and trafficability of such land surfaces, hydrologic predictions of flow and transport processes are seriously hampered. Changes in soil volume and pore space induced by shrink-swell behavior present a challenge to the development of predictive models for flow and transport, in particular to the development of constitutive hydraulic functions. Despite well-developed theory for crystalline and osmotic swelling of clay minerals, translation of lamellar-scale theory to formulation of constitutive hydraulic functions is lacking.

The objectives of the proposed study are based on the long term goals to develop a fundamental understanding and accurate description of water and solute behavior in environmental and agricultural systems with appreciable amounts of clay minerals, and to provide enhanced quantitative tools for environmental and agricultural management practices to control surface runoff, leaching, soil erosion, salinization, and sodicity. This requires the development of physically based pore- and sample-scale models for liquid retention and hydraulic conductivity considering the swelling and shrinking behavior of clay minerals. Within this context the specific objectives of the project were to:

(1) Develop a model for geometry and changes in clay fabric pore space with hydration state, clay mineralogy, and solution composition.

(2) Incorporate other textural fractions (e.g., sand, silt) toward developing a complete pore scale model for clayey soils.

(3) Derive hydraulic functions for clay fabric and simple sand-clay mixtures

Methodology:

The framework for modeling pore space changes is based on consideration of the soil clay fabric as an assembly of colloidal-size tactoids with lamellar structure. The arrangement of clay tactoids and the spacing between individual lamellae are functions of clay hydration state quantifiable via the disjoining pressure, dominated by a large electrostatic repulsive component. The DLVO theory developed by Derjaguin and Landau [1941], and Verwey and Overbeek [1948] was applied to derive relationships between lamellae spacing and bulk matric potential.

Silt and sand textural constituents are represented as rigid spheres interspaced by clay fabric in two basic configurations of "expansive" and "reductive" unit cells. Bulk soil properties such as clay content, porosity and surface area serve as constraints for the pore-space geometry. Liquid saturation within the idealized pore space is calculated as a

function of chemical potential considering volume changes due to clay shrink-swell behavior. Closed-form expressions for prediction of saturated hydraulic conductivity are derived from calculations of average flow velocities in ducts and between parallel plates, and invoking proportionality between water flux density and unit hydraulic gradient.

A flexible wall permeameter is used to measure saturated hydraulic conductivity of clay-sand mixtures. Feedback from measurements is used for evaluation and refinement of the theoretical modeling efforts.

Principal Findings and Significance:

We made significant progress in developing a pore space evolution model and derived physically based analytical solutions for liquid retention and saturated hydraulic conductivity as a function of soil chemical potential. Preliminary model calculations compare favorably with published data, and show great potential for upscaling considerations. The findings of this project were published in the Journal of Hydrology and disseminated through numerous invited presentations.

A NSF-EPSCoR equipment grant also allowed us to purchase a state-of-the-art flexible wall permeameter. We started a series of measurements to determine effects of clay type, clay content, electrolyte type, and electrolyte concentration on hydraulic properties of clay-sand mixtures. These data are quite unique and extremely valuable for refinement and evaluation of our modeling approach. Everybody dealing with clays is aware that experiments are extremely time consuming and complicated due to the swelling behavior. Nevertheless we were able to develop sample mixing and saturation procedures that allow repeatable series experiments.

Future work will include a comprehensive measurement series and the development of a physically based upscaling scheme for sample and profile scale predictions of hydraulic conductivity.

The developed modeling framework offers a means for systematic data collection and a unified representation of important hydraulic properties of swelling porous media that otherwise involve inseparable and often competing processes.

Additionally, results of this study should benefit water management in swelling soils leading to improved infiltration and water use efficiency. Due to the sensitivity of clay soils to irrigation water quality, a framework such as developed could benefit salinity and sodicity management by quantifying the impact of irrigation strategy on soil hydraulic properties. At the extreme end of these considerations are insights on clay dispersion and surface sealing with potential for soil erosion, and colloidal-facilitated transport of agro-chemicals. Another area of potential application is the design of clay liners for hydrologic isolation of waste disposal sites. Improved understanding of hydrologic processes in clayey formation becomes increasingly important for the design of nuclear waste repositories currently under consideration in the Boom Clay formation in Belgium and in a similar formation in Switzerland.